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Structural classification of galaxies in clusters

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Abstract. The traditional method of morphological classification, by visual inspection of images of uniform quality and by reference to standards for each type, is critically examined. The rate of agreement among traditional morphologists on the morphological type of galaxies is estimated from published classification works, and is estimated at about 20 %, when galaxies are classified into three bins (E, S0, S+Irr).

The advantages of the quantitative method of structural classification for classifying galaxies in clusters are outlined. This method is based on the isophotal analysis of galaxy images, and on the examination of quantitative structural parameters derived from this analysis, such as the profiles of luminosity, ellipticity and deviations from ellipticity of the galaxy.

The structural and traditional methods are compared on a complete sample of 190 galaxies in the Coma cluster. The morphological types derived by both methods agree to within 15 or 20 %, the same rate as among traditional morphologists alone, thus showing that our morphological classes do coincide with the traditional ones. The galaxies with discrepant types are mostly faint ($\mathrm{mag}_B > 16.0$), or have features typical of spirals, but which have not been detected, noticed or taken into account by traditional morphologists. The rate of agreement is also good for galaxies in a distant cluster ($z \sim 0.4$).

The structural method, which requires an image quality adapted to the difficulty of classifying a given galaxy, gives highly reproducible results, never reached by traditional estimations of the morphological type. Thus, the morphological types obtained with this method should be preferred, even if their determination is more time and telescope consuming, because they are less subjective, therefore more reproducible, and based on images of adequate resolution. The advantages of the method are further demonstrated by new results on the properties of galaxies in clusters.

Key words: Galaxies: fundamental parameters; elliptical and lenticular, cD; spiral; clusters: Coma cluster

1. Introduction

Classification is the first task to be undertaken when exploring a new field. A good classification system should separate the bewildering diversity of observed shapes into a finite number of bins containing objects with specific physical properties, and thus provide a better understanding of the physical nature of the objects under investigation. In order to do so, this system should be based on structural properties, and should ignore others, even if they are aesthetically pleasing. The classification criteria should also provide a non ambiguous assignment to a class for each object; more than one criterion per class may lead to two equally possible classifications for a given object.

The morphological classification of galaxies first proposed by Hubble (1936) has been universally adopted with little change and is still being used, because it does break galaxies into classes with specific physical properties. Its application to galaxies in clusters has revealed a morphological segregation of galaxies which is probably a key element for understanding the formation and evolution of galaxies, and the investigation of the luminosity function for each morphological type should shed further light on this question. The refurbishing of the Hubble Space Telescope (*HST*) has renewed interest in the morphological classification of galaxies, as it will enable us to compare the morphological composition of nearby and distant ($z \simeq 0.2-0.4$) samples, and thus to obtain information on the evolution of galaxies.

While the work of classifying galaxies has traditionally been done by visual inspection of images of galaxies, recent progress in the fields of digital detectors and image treatment by computer has given rise to new methods of investigation of galaxy images, such as isophotal analysis (e.g. Poulain, Nieto & Davoust 1992, Michard & Marchal 1993), which in turn has lead to further refinements of the classification system. Such refinements might not necessarily bring out new physical idiosyncrasies of galaxies; indeed, it still remains to be shown that the dichotomy of elliptical galaxies into boxy and disky breaks these galaxies into two subclasses with physically distinct internal properties (Andreon 1996). The new perspectives opened by computer treatment of images should nevertheless be pursued, as computers eliminate part of the subjectivity in the task of classifying galaxies.

In this paper, after analyzing the traditional morphological classification system (Sect. 2) and its problems (Sect. 3 and 4), we present a quantitative method for classifying galaxies in clusters, based on the analysis of quantitative structural parameters, such as the luminosity, ellipticity and e_4 profiles (Sect. 5). We show that this method is identical in spirit to the traditional system by comparing the morphological types

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obtained by both methods for a large sample of galaxies in the Coma cluster (Sect. 7) and for galaxies at high redshift (Sect. 8). The justification for preferring our method is that it has the advantage of giving highly reproducible results and requires a uniform resolution in the restframe of the galaxies, at least for the most difficult cases, and that it has already demonstrated its merits (Sect. 6).

2. Traditional morphologists' classification

Most of our present knowledge of galaxy morphology is based on the pioneering works of a few observers who classified thousands of galaxies. The observational material available for the classification (better material allows a more detailed scheme) and the aims of the classification work generally govern the choice of the classification scheme. The details of these schemes depend on the authors; nevertheless, some points are common to most authors.

1. The morphological 'system is usually defined by a set of standards or prototypes' (Buta 1990), and the galaxies are classified according the resemblance to these standards (although it is not always the case; see e.g. Kormendy 1979, Kennicutt 1981 or Schombert 1986).
2. The observational material used for classifying galaxies is very often photographic plates (or copies of them). Historical reasons and the large angular extent of plates with respect to CCDs made this choice obligatory for large samples of galaxies as well as for galaxies larger than a few arcmin.
3. Almost all galaxies are on the same plate or on very similar plates exposed under similar observing conditions (seeing, sky level, etc.). The observational data are thus uniform, i.e. the quality of the observational material is the same for the whole sample.
4. Structural components (disk, bar, etc.) are not measured by most morphologists (Hubble's definition of types does not require such a measurement), but only visually estimated. Up to now, it was not reasonable, in terms of computer time, to measure such structural components for large samples of galaxies: morphologists take 30 sec. to classify a galaxy (Naim et al. 1995), whereas, for example, the determination of the Hubble type by means of structural components (see Sect. 5) may reasonably take 30 min. per galaxy.

3. Problems with the traditional classification scheme

The traditional classification method, by visual inspection of plates and by reference to standards for each type, has been very successful in many fields of extragalactic astronomy. However this method suffers from drawbacks, which can become serious, depending on the use one makes of the morphological types.

First, the reference to standards makes the morphological classification difficult enough that it resembles 'more an art than a physical measurement' (Buta 1990). This task is thus not accessible to most of the astronomical community, since, to accomplish it, one has to be an expert morphologist.

The strong subjectivity of the task raises the question of its reproducibility and of the consistency of the morphological types determined by different morphologists. The latter question has been addressed by Lahav et al. (1995). Less than 1 % of the large galaxies ($D_{25} > 1.2$ arcmin) have the same morphological label when galaxies are classified in 16 bins by 6 well known morphologists. The cause of the disagreement is not tied to differences in the images that the morphologists studied, since they used the same images. The question of consistency will be discussed further in Sect. 4.

The fact that structural components (bar, disk, bulge, arms, etc.), which astronomers naturally think of when speaking of morphological types, are not measured quantitatively and in some cases not even detected by traditional morphologists introduces differences and biaises between the presence of such structural components and the resulting morphological types. These differences and biases could be important or negligible, depending on the study undertaken, on the fraction of galaxies for which one or several structural components were missed, and on how this fraction was classified.

Second, the uniformity of the observational material is not a desirable property when the studied sample contains galaxies at different distances, of different sizes or luminosities and/or projected at different angles on the sky.

1. Due to the limited dynamical range of plates, images of very bright galaxies are saturated and images of faint galaxies are of too low quality to allow any classification. As repeatedly stated by morphologists, this happens very often: in one third of the cases for a sample of galaxies larger than 1.2 arcmin (Lahav et al. 1995, Naim et al. 1995) and, more generally, in 85 % of the cases (Buta 1992). This problem does not appear very often in the output catalogue; in other words there is no trace in the catalogue that some of the galaxies have classification problems. Buta (1992) stressed that 'it is important when using published morphological types to know where their types came from and their limitation'. Finally, as morphologists themselves admit (Lahav et al. 1995), they mostly classify galaxies for which they do not have suitable data. In particular for galaxies in nearby clusters, Dressler (1980) remarks that sky survey plates are not good enough for morphological classification and that Cassegrain plates (or prime focus plates from a large reflector) must be used.
2. The morphological label attributed by morphologists to the observed galaxies unfortunately depends on the projection angle of the galaxy on the sky. It is a well known fact that face-on S0 galaxies are missing in all catalogues of galaxies, because they are misclassified as E (van den Bergh 1990). The detectability of bars, arms, disks of galaxies depends strongly on their projection angle on the sky, as well as on the resolution of the observations used to perform the classification (for disks, see e.g. Nieto et al. 1994, whereas for bars see e.g. de Vaucouleurs & Buta 1980 and Nieto et al. 1992).

The drawback of using uniform data becomes obvious in studies of galaxies in more than one cluster, when the observed galaxies are not all at the same distance. Andreon (1993) showed that the spiral fraction in nearby ($z < 0.05$) clusters measured by Bahcall (1977) decreases as the redshift increases, reaching a null value at $z = 0.05$. Such behavior (a sort of inverse Butcher-Oemler effect) is not intrinsic to the observed clusters, but is only a consequence of the increasing difficulty of identifying spiral galaxies as the redshift increases. A similar artificial trend has already been pointed out by Tammann

(1987) for explaining the apparent rise of the Hubble constant with redshift from independent data. Such a feature is common (and has been overlooked) in the literature. Unfortunately, much of our knowledge of nearby clusters is based on such data (e.g. Sarazin 1986, Edge & Steward 1992).

Another problem linked to the resolution, which we discovered when studying a distant cluster observed with *HST* (Andreon, Davoust & Heim 1996), is that of the sampling of the image. The point spread functions of two images may have the same FWHM, but if the first image is oversampled and the other one has a pixel size comparable to the FWHM of the point spread function, morphological details will be lost in the latter image. Thus, as one classifies more distant galaxies, both the resolution *and* the sampling of the image should increase.

The use of uniform data (i.e. plates) and of images whose dynamical range is limited, is an easy way of collecting large numbers of morphological types, but it is also likely to induce misclassifications. The images should have a quality adapted to the difficulty of the galaxy classification.

4. Rate of agreement among traditional morphologists

We have no way of estimating the stability of the morphological classification, defined as the fraction of galaxies given the same morphological type when observed twice with the same observational material by the same morphologist. However we can estimate the effect of the subjectivity of the Hubble types' definition and how it is related to the quality of the observational material by measuring the reproducibility of the Hubble type estimate in the cases when only the morphologists differ, when only observations differ and when both differ.

Table 1. Agreement on the Hubble type estimates

Different morphologists	
Large galaxies	40 % - 85 %
HST images of distant clusters	∼80 %
Different images	
Large galaxies	∼80 %
HST images of distant clusters	∼80 %
Different images and morphologists	
Coma galaxies: Dressler *vs* Butcher & Oemler	88 %
Coma galaxies: Dressler *vs* Rood & Baum	84 %
Coma galaxies: Dressler *vs* RC3	73 %

4.1. Different morphologists

We start with the results of a comparative classification exercise performed among expert morphologists using the same images (Lahav et al. 1995, Naim et al. 1995). Six expert morphologists classified 835 (nearby and large) galaxies in 16 classes. All the morphologists looked at exactly the same laser printed images, except for one, who looked at images on a computer screen.

The solid line in the left panel of Fig. 1 shows the relative agreement (in %) among morphologists (grouped by pairs) on the morphological type of a given galaxy. This agreement is measured by the fraction of galaxies (among 835) given the same coarse Hubble type (E, S0, or S+Irr) by a pair of morphologists. We put the galaxies in one of the three bins according to the T value listed in Naim et al. (1995). The fraction of galaxies given the same morphological type ranges from ~ 40 % to ~ 85 %, depending on the pair of morphologists, with a mean of ~ 50 %.

The dotted line in the same panel shows the relative agreement for easily classified galaxies (i.e. for galaxies whose morphological type is not followed by a colon or question mark). This is the fraction of galaxies (among the ones easily classified by both morphologists of a pair) that were given the same coarse Hubble type by both morphologists. The agreement is much better, of the order of 90 %, which is normal, since the task is admittedly easy.

The right panel of Fig.1 shows that this good agreement in fact only concerns a minor fraction, 50 % and often less, of the sample. It does not show how often pairs of morphologists agree on the type of a galaxy, but how often they agree on whether the galaxy is easy to classify or not. This fraction of galaxies which are easily classified by pairs of morphologists (i.e. whose type is not followed by a colon or question mark for either morphologist of the pair) is rather small. On this small fraction the agreement on the type is excellent.

Furthermore, part of the agreement among morphologists is due to chance, since we have reduced the number of bins from 16 to 3.

Dressler and Oemler classified the galaxies of the Abell 851 cluster from the same *HST* images before refurbishing (Dressler et al. 1994a). Couch, Sharples and Smail did the same for the galaxies of Abell 370 (Couch et al. 1994). In both cases, the disagreement among morphologists on the assignment of the morphological type was about 20 to 25%.

4.2. Different images

We now compare the estimates of a morphologist looking at different images. Dressler et al. (1994b) classified twice the galaxies of the distant cluster Cl 0939+4713 observed with *HST*, before and after refurbishing. Taking the types of galaxies from their Fig. 4, we find that 20 % of the galaxies have different coarse Hubble types.

Naim et al. (1995) and we find a similar rate of disagreement between the morphological types assigned by de Vaucouleurs (Naim et al. 1995) and by RC3 (de Vaucouleurs et al. 1991) for the sample of 835 galaxies.

4.3. Different morphologists and images

The agreement, when both morphologists and images differ, can be estimated from the published morphological types of galaxies in the Coma cluster. We take Dressler's (1980) morphological type as reference, because it concerns a larger and deeper sample than the others. The agreement between Dressler (1980) on the one hand, and other morphologists (Rood & Baum 1967, Butcher & Oemler 1985) and RC3 (de Vaucouleurs et al. 1991) on the other, on the types of Coma galaxies is shown in the last three rows of Table 1. The agreement, for classifications based on different observational materials, is relatively good, even if our comparison is biased by the fact that low values of the agreement are not permitted

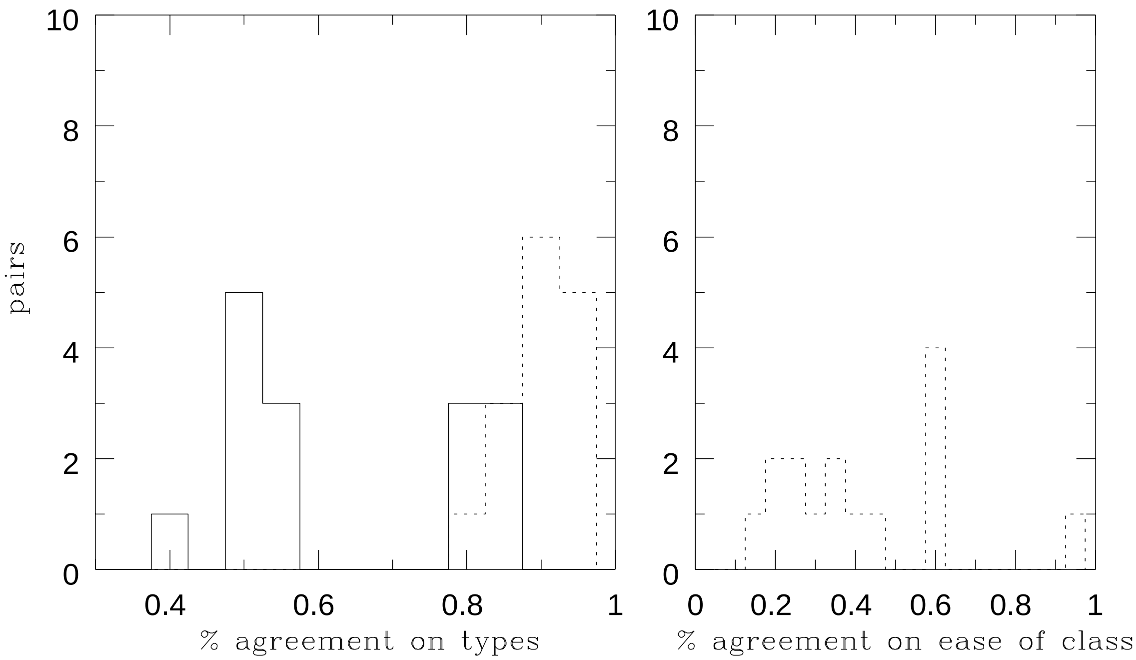

Fig. 1. Left panel: relative agreement among pairs of morphologists on the morphological types, for the whole sample of galaxies (solid line) and for easily classified galaxies only (dotted line). Right panel: relative agreement among pairs of morphologists on whether a galaxy is easy to classify.

because of the small number of classes which naturally induces some chance agreements. We have checked that the chance agreement can be as large as 35 % to 75 % depending on the morphological composition of the sample and on the exact way in which we randomly classify the galaxies (conserving or not the morphological composition of the sample).

These three comparisons, when only morphologists differ, when only images differ and when both differ, show that about 20 % of the galaxies have an unprecise Hubble type. This inaccuracy arises because of the quality of the material used for the morphological estimation and/or because of the subjective nature of morphological classification. The fraction is even larger if galaxies are classified from Schmidt plates.

5. Classifying by means of structural components

In view of the drawbacks of the traditional method, especially when applied to the specific task of classifying galaxies in clusters, other methods have been introduced. Most of them have the advantage of giving a stable estimate of the Hubble type, in particular when prototypes or training sets are kept fixed, but they ultimately infer the Hubble type from the galaxy properties by using the fact that the Hubble type is correlated to the galaxy properties (colors, bulge on disk ratio, spectral shape, etc.). The observed properties of galaxies in classes defined in this way are strongly influenced by the constraints used to define the classes; for example, if colors are used for classifying galaxies, blue ellipticals will be missing whether they exist or not in the Universe. We are thus not in favor of adopting such methods.

We propose using an alternative classification method based on the criteria presented in Michard & Marchal (1993) and adopted with minor changes in Andreon et al. (1996). This method relies on the detection of structural components, rather than on the resemblance to standards.

The morphological classification is done as follows. A number of radial profiles (of surface brightness along the major and minor axes, of ellipticity, of the position angle, of isophote deviations from the perfect elliptical shape) are computed and then visually inspected for the detection of signatures typical of the morphological components described below. When a component (a disk, a bar, an envelope, etc.) is detected, we take note of it.

The segregation between the E and S0 types is based upon the examination of the surface brightness profile along the major axis of the projected galaxy, plotted on an $r^{1/4}$ scale. The presence of a disk gives a characteristic bump above the linear profile which characterizes pure spheroids. This photometric signature of S0s should not be confused with other often observed deviations from the de Vaucouleurs law, both in giant ellipticals with an envelope enhanced above the extrapolated $r^{1/4}$ line, and in minor objects with evidence for a cut-off below this line (Schombert 1986). This signature may be absent in some face-on S0s, which are then classified as Es; there is no way of avoiding this type of misclassification, as shown by the photometric similarity between the face-on NGC 3379, prototype of Es, and the edge-on NGC 3115, prototype of S0s (Capaccioli et al. 1991). Round galaxies with elliptical isophotes and exponential profiles are classified as S0s. In this spirit, these criteria are identical to those used in classical morphol-

ogy, when the observer looks for subtle changes of gradient in a galaxian image.

The E galaxies are further subclassified into 'disky', or diE, 'boxy', or boE, and 'undefined', or unE. This is done mainly from the radial profile and sign of Carter's e_4 coefficient*. Roundish galaxies where the e_4 values fluctuate around zero are classified unE. To this class also belong Es with inner disky and outer boxy isophotes (or vice versa), and lemon-shaped Es. Note however that non zero e_4 are also produced by the presence of dust and shells, which also give a signature in higher-order coefficients and in the two-dimensional image.

The S0s are subclassified into the SA0, SAB0 and SB0 families, based upon the radial profile of the position angle (PA) of the isophotal major axis. For a galaxy observed with a sufficient resolution, the PA of the bulge and disk are nearly the same, while the PA of the bar stays in a limited range (except in cases of unfavorable projection). At the distance of nearby clusters ($v \sim 5000 - 7500$ km s^{-1}), it often happens that the contrast between bulge and bar is washed out by the seeing.

The segregation between S0 (or E) and S is based on the presence of spiral arms or very irregular or asymmetric isophotes. Because of this choice, the spiral class defined in such a way may include (a small number of) galaxies showing strong signs of interaction (tidal arms, double nuclei, non concentric isophotes, etc.). On the one hand, such a misclassification could be viewed as a contamination of the 'pure' spiral class; on the other hand, interacting galaxies often show important star formation. But in no case should we introduce another class, that of interacting galaxies, because this goes one step beyond that of classification, since we then interpret peculiarities in terms of gravitational interaction.

Spiral galaxies are not classified in more subclasses than S and Irr for two reasons. First of all, we lack an objective and unique method to distinguish stages in the S class. As noted by Sandage (1961), Hubble's (1936) description of spirals does not allow a unique classification of some spirals (e.g. NGC 4941) and some criteria have to be relaxed (Sandage, 1961, p. 13). Furthermore, splitting the S into the traditional stages does not separate galaxies of different physical types, since each stage is a blend of galaxies showing a range in properties, sometimes as large as the one found among the stages (see, e.g., Gavazzi & Trinchieri 1989, Roberts & Haines 1994, and Staveley-Smith & Davies 1988).

Finally, we stress that the structural classification scheme does not (implicitly or explicitly) use any other structural parameter, different from the ones above, to classify the galaxies; in particular, it does not make use of the bulge to disk ratio to discriminate between lenticulars and spirals.

In summary, the galaxy morphological type is nothing else than the obvious composition of morphological components detected following the rules outlined above. For example, a galaxy having (almost perfect) elliptical isophotes with a bump in surface brightness along the major axis and a characteristic twist of the position angle, is noted as having a photometric disk, a bar and no spiral arms, and therefore is classified as SB0.

* The e_4 coefficient characterizes the deviations of period $\pi/2$ and phase 0 of the isophote shape from the perfect ellipse. Galaxies with positive e_4 show a luminosity excess along the major axis interpreted, as for S0 galaxies, as revealing the presence of a disk. A negative e_4 coefficient indicates boxy isophotes.

For this galaxy, whether it is boxy or disky is not a matter of concern, since boxiness or diskiness have no effect on its morphological type.

The Hubble sequence therefore looks like this :

detailed types:	boE unE diE	SA0 SB0	S Irr
coarse Hubble types:	——E——	—S0—	—S—

The criteria of structural morphology are as close as possible to those of morphologists. The main difference is that structural components are measured, and galaxies are classified according the presence (or absence) of these structural components *without exceptions* and that galaxies are not classified according to the resemblance to standards. This alternative approach has several advantages.

6. Advantages of the structural classification scheme

6.1. Low subjectivity

In the first step of the classification work, where we compute the various profiles, the only (very minor) subjective task is to select foreground or background objects to be masked because they contaminate the galaxy brightness.

The second step, the visual detection of the morphological components, is still partly subjective, in particular when we are classifying galaxies on the borderline between classes. But nothing prevents us from making this part of the analysis automatic, by introducing profile templates which mark the expected behavior for the morphological components, thus making it fully objective and reproducible. However, the complexity of Nature, which produces galaxies with disks, halos, bulges and bars with a variety of ellipticity and surface brightness profiles, and which mixes them and shows them to us projected on the sky under different angles, makes this *automatic* approach too complex just for determining the morphological type.

The third step of the classification method, assembling the structural components to derive the morphological type, is of course fully automatic.

The subjectivity arising from the visual detection of morphological components in our method is always lesser than in the traditional estimation of the types, since the detection of morphological components is easier on profiles than on direct images. Therefore, the number of difficult cases of classification is reduced. For example, deviations from de Vaucouleurs' law are easily visible on a surface brightness vs. $r^{1/4}$ profile, used by us, much more so than on direct galaxy images, used by classical morphologists. This allows us to detect disks in many almost face on S0s. In fact, the ellipticity distribution of Dressler's (1980) S0s in Coma shows a clear bias against round (face-on) galaxies (Michard 1996). Using our criteria to classify the galaxies, 1/3 of Dressler's (1980) Es move into the S0 class, thus strongly reducing the bias (Michard 1996).

The residual role played by the subjectivity can be estimated by comparing the rate of agreement among Hubble types estimated by different authors from the same galaxy profiles.

6.2. Reproducibility

A more objective method should produce highly reproducible results. To check the reproducibility, and to understand the effect of any personal judgment on the morphological estimate, (at least) two authors classified a large subsample of galaxies in Coma independently, after a period of training. The galaxies to be classified had magnitudes in the range 12 to 17 B mag and their images had a typical seeing in the range 0.35 to 3 arcsec (see Andreon et al. 1996 for details). We had both CCD and digitized plate images available for classification. For this comparison, the images considered and all derived data (profiles of surface brightness, ellipticity, position angle, e_4, etc.) were exactly the same.

A perfect agreement on the coarse Hubble type was found for all (more than 100), but two, galaxies. The two discrepant galaxies are peculiar: a very dusty galaxy (GMP 1646) with an $r^{1/4}$ profile (elliptical or irregular?) and a dusty asymmetric lenticular (or spiral?) (GMP 1204).

The fact that, in the traditional morphological analysis, 15-20% of the galaxies have different morphological estimates introduces a scatter in the properties of the Hubble types *precisely because of the highly subjective nature of the type estimate* and this can mask real differences between the properties of the morphological types. With the reproducibility of 95% reached by our estimate of the type, only a small fraction of galaxies are not of the type assigned by us; this greatly reduces the scatter in the properties within classes and allows an easier comparison of the types in different locations in the Universe (cluster vs field, nearby vs distant, etc.) and greatly helps detecting previously unnoticed properties of the morphological types.

6.3. Stability with respect to observing conditions

To understand whether different telescope set-ups, seeing conditions, filters, and other effects affect our morphological classification, we observed the same subsample of galaxies in Coma during different runs, at different telescopes, with different filters (mainly Johnson V and Gunn r) and detectors (4 CCDs and one plate). Different images of the same galaxy were classified by the same or by different observers. Once the observing conditions are taken into account, there is perfect agreement on the coarse Hubble type and on the detailed type of the galaxies for all 54 comparisons done, but for GMP 1300, classified as S from our plate and S0 from our CCD image. Typical differences tied to observing conditions are due, for example, to the limited field of view of observations at the 3.6m Canada-France-Hawaii telescope in Hawaii (CFH), preventing one from classifying galaxies larger than the CCD field of view, or to the lower resolution of the prime focus plate used (FWHM=1.8″) compared to the best quality CCD images. The comparison of the CFH observations taken under excellent seeing conditions (FWHM=0.35″) with observations at the 2m telescope of the Pic du Midi Observatory taken under good to fair seeing conditions (0.8″<FWHM<1.5″) for common galaxies shows that Pic du Midi observations are good enough for determining the galaxy type, since not one galaxy (out of 13) was classified in two different coarse classes from the two observing materials (again, once the small field of view of CFH observations is taken into account). The CFH images certainly allow one to classify E galaxies more easily into the three families and to detect small morphological components, such as dust lanes.

6.4. Ability to bring out new properties of galaxies in clusters

Our morphological scheme, *whatever it traces*, gives highly reproducible results and is not very sensitive to the observing conditions, provided the resolution is adapted to the difficulty of the galaxy classification. But this does not necessarily mean that our method brings galaxies into classes containing objects with similar physical properties better than the traditional classification scheme.

The *relative* quality of our classification method can only be judged on its results, i.e. on the ability of our scheme to separate galaxies of different *physical* types into different classes, and to bring out new properties of galaxies in clusters.

This ability is demonstrated by a series of recent results obtained with this method. For example, we have detected a segregation of the morphological types *stronger* than the usual clustercentric or density segregations in the Perseus (Andreon 1994) and Coma (Andreon 1996) clusters and in the distant cluster Cl0939+4713 (Andreon, Davoust & Heim 1996). Es have a fainter mean surface brightness than S0s in Coma (Andreon 1996) and Cl0939+4713 (Andreon, Davoust, Heim 1996). Furthermore, by using images of resolution adapted to the difficulty of classification, we have found that the spiral fraction rises by a factor 2 or 3 in the Perseus and Coma clusters (Andreon 1994, 1996) and, by indirect evidence, in most nearby clusters (Andreon 1993), but not in the distant cluster Cl0939+4713; this strongly reduces the evidence for a morphological evolution of galaxies in clusters that many observations make unreasonable (see Andreon 1993, and Andreon, Davoust & Heim 1996 for details).

7. Comparison between structural types and traditional ones

In order to assess the relation between our morphological types and the 'traditional' ones, we now present a detailed comparison between our types and published ones for galaxies in the Coma cluster. Because of the scarceness of Es and S0s classified into detailed classes (diE/boE, SA0/SB0), mainly in the comparison samples, but also in ours, we can only estimate the quality of the broad Hubble types (E,S0,S).

This comparison of Hubble type estimates is based on a magnitude complete sample of 190 galaxies in Coma brighter than $mag_B = 16.5$ mag and within one degree from the cluster center. Types determined by structural morphology are presented in Andreon et al. (1996) and Andreon et al. (in preparation), traditional types are taken from the literature. In summary, our structural classification is based on (digitized) Schmidt plates for obvious spirals and on the 'quantitative analysis' of a digitized KPNO 4m prime focus plate, of CCD images taken under good or excellent seeing conditions at Pic du Midi and CFH for all the other types (as well as for non obvious spirals). Significant overlap exists among our observations, allowing us to assess the relative quality of the classifications (Sect. 6.3). For the classifications from the literature, particular attention was paid to the meaning given to the type notation by each morphologist: for example, the S0/a type is the intermediate type between S0 and Sa types for some

authors *and* a sign of the inability to discriminate between the two types for others.

7.1. Saglia, Bender & Dressler (1993)

Saglia, Bender & Dressler (1993, hereafter SBD) determined the coarse Hubble type of galaxies in Coma following a morphological scheme similar to ours, in the sense that structural components of galaxies are measured, and not visually estimated. They take however a conservative approach, changing the traditional type of the galaxies only when their analysis shows that the type listed in Dressler (1980) is wrong.

Table 2 shows the results of the comparison of SBD's Hubble types with ours for common galaxies.

The fraction of discrepant types is 15 % (7 galaxies out of 47).

– One galaxy (GMP 1201) was classified as S0 by us (and by all the other morphologists, including Dressler) and S by SBD.

– Out of the two galaxies classified E by SBD and S0 by us, one (GMP 1878) shows a faint but extended disk, and is certainly not a boE, as our $0.35''$ resolution CFH images show, and the other one was assigned the same type by us from the analysis of two independent images. All the other galaxies with discrepant types are faint ($\mathrm{mag}_B > 16.0$) and have low contrast spiral arms, and were thus classified as S0/a by us and S0 by SBD.

The fraction of discrepant types (15%) is very low, and fully understood but for two galaxies out of 47 (4 % of the sample).

Table 2. SBD vs us

SBD /us	E	S0	S
E	19	2	0
S0	0	18	4
S+I	0	1	3

7.2. Butcher & Oemler (1985)

Butcher & Oemler (1985, hereafter BO) classified galaxies in the Coma cluster core by inspection of a Schmidt plate (scale $\sim$ 65 arcsec mm^{-1}) and/or of an unspecified "4m telescope" plate. Their classification scheme has a fine resolution for bright and large galaxies, and a coarse one for faint ($\mathrm{mag}_J > 15.5$) galaxies and for galaxies difficult to classify (e.g. face-on S0s). At their intermediate resolution, which corresponds to our coarse Hubble types, most of the galaxies have been assigned a Hubble type by BO, whereas a small percentage could not be put in a single class by BO (some galaxies that are noted as EL, i.e. E or S0). BO put the S0/a galaxies in the S bin in the intermediate and coarse resolution schemes (see their Table 12). Since we use their intermediate resolution, we put our S0/a in the S bin for the purpose of comparison.

Table 3 shows the results of the comparison of the morphological types for common galaxies. Out of 123 galaxies in common, 23 (=19 %) have discrepant Hubble types.

– Out of the 8 early-type galaxies with discrepant types, four (GMP 999, 1035, 694, 552) are faint ($\mathrm{mag}_B \sim 16$), two (GMP 1373 and 908) have an uncertain type in our work, one (GMP 565) has a disk but not bright enough to allow one to classify it as S0, in spite of BO's S0 classification, and finally our data for the last galaxy (GMP 1834), classified as E by BO, suggest the presence of a small bar (undetected by BO) which lead us to classify this galaxy as SAB0.

– Out of the 15 galaxies classified as S0 by BO and as S by us, 7 show a spiral pattern not resolved into spiral arms and without HII regions on our CCD images. Such faint features were probably not detected on BO's plates, or judged of null importance by them for the classification.

The galaxies with discrepant types are not distributed uniformly among the Hubble types. As a consequence, the morphological composition of the cluster differs in the two works, *even though* the sample is composed of the same galaxies. The spiral fraction (here defined as the ratio of the number of spirals to the total number of galaxies) in Coma's core rises from 17 %, when computed with BO's morphological types, to 26 % when computed with our types.

Table 3. Butcher & Oemler vs us

BO /us	E	S0	S
E	23	3	0
S0	5	48	15
S	0	0	20
n.c. (EL)	3	6	0

Table 4. Dressler vs us

Dressler /us	E	S0	S
E+D+E/S0	31	12	0
S0+S0/a	9	58	11
S+I	0	3	29

7.3. Dressler (1980)

Dressler (1980) classified the Coma galaxies in a slightly larger region than ours, by inspection of a plate taken at the Cassegrain focus of a 2.5m telescope (scale $\sim$ 10.9 arcsec mm^{-1}). His sample is the largest one in the literature for Coma galaxies. It is part of the largest published survey of morphological types of galaxies in nearby clusters. The plates used by Dressler have one of the smallest scales, and therefore meet our first requirement, to be of good quality. Dressler's types have been widely used in the literature for studies of morphological segregation (e.g. Whitmore & Gilmore 1991, Whitmore et al. 1993, Sanromà & Salvador-Solé 1990), and most of our knowledge on morphological segregation of galaxies in clusters rests on data listed in this catalogue. Dressler's X/Y notation for types points out his care in not definitely classifying galaxies for which he does not have suitable data (Dressler 1980). Therefore Dressler's X/Y types are not meant to be a transition type between X and Y.

Table 4 shows the comparison of types for common galaxies. We put Dressler's E/S0 and D types in the same bin as the E.

As for previous comparisons, we put Dressler's S0/a galaxies and ours in the S class, but consider them separately in the following discussion. The fraction of discrepant types is 23 % (35 galaxies out of 153).

– 9 of Dressler's S0s were classified as E by us; most of them are roundish galaxies difficult to classify because face on.

– 12 of Dressler's E (+D+E/S0) were classified as S0 by us, of which 6 are faint galaxies, 5 were classified by Dressler as E/S0 (i.e. E *or* S0) and the last one (GMP 1931) is a barred galaxy.

– 11 of Dressler's S0 (+S0/a) were classified as S by us. The fact that at least 7 of them just have a spiral pattern not resolved into arms and HII regions in our images suggests that low contrast spiral arms are not detected or are considered of null importance in Dressler's morphological scheme.

– Two of Dressler's Sa galaxies (GMP 1925 and GMP 1844) and one S0/a (GMP 1154) were classified as S0 by us. Dressler's S0/a (i.e. S0 or Sa), classified S0 by us, is not a discrepant case since Dressler's classification is uncertain. Furthermore our images of this galaxy show a slight asymmetry that may explain why Dressler's classification is uncertain. The two other galaxies show uncommon characteristics of lenticulars, an isophotal twist in the outer envelope (GMP 1925) and an important ring-lens (GMP 1844). It is possible that Dressler used such characteristics to classify the galaxies as S, because they do not present spiral arms or dust on our images. In such a case, the differences in the morphological estimates are due to the different weights given to structural components in the definition of the galaxy types.

The fraction of discrepant types is 23 %, (at least) half of which are accounted for by galaxies difficult to classify, and the other half by different weights given to the presence of a spiral pattern or other morphological structures in classifying galaxies.

7.4. Rood & Baum (1967)

Rood & Baum (1967, hereafter RB) classified the galaxies in the Coma cluster by visual inspection of a prime focus plate from the 5m Palomar telescope (scale ~ 27 arcsec mm^{-1}).

Table 5 shows the comparison of RB's morphological types and ours for galaxies in common. We put the S0/a galaxies in the S bin as in previous comparisons, and consider them separately in the following discussion.

– Five of the 6 early-type galaxies with discrepant types are faint. The last one, classified E by us and S0 by RB, is the second ranked galaxy of the Coma cluster. RB probably classified it as S0 because it has an outer envelope, which identifies this galaxy as an S0 according to Hubble's definition of S0.

– All the other discrepant types concern RB's S0s classified as S by us. Since RB used similar plates to ours (with similar scales), they probably did not miss the structural components that we detected on these galaxies, but they presumably judged these components of null importance for the classification. We note, furthermore, that the missed spirals do not have obvious spiral arms or HII regions but just a spiral pattern. From the classical morphologist's point of view, these galaxies do not resemble the standard Sa, which explains their classification as lenticulars.

The fraction of galaxies with a discrepant type is 16 %, if we put the S0/a in the S class, or 12 % if we put the S0/a in the S0 class, as RB seem to do.

Table 5. Rood and Baum vs us

RB /us	E	S0	S
E	20	5	0
S0	1	24	10
S	0	0	5

Table 6. RC3 (all RC3 Coma galaxies) vs us

RC3 /us	E	S0	S
E	22	5	0
S0	7	17	9
S	1	2	16
n.c.	13	39	19

Table 7. RC3 (bright RC3 Coma galaxies) vs us

RC3 /us	E	S0	S
E	18	2	0
S0	6	10	6
S	1	1	9
n.c.	1	3	3

7.5. RC3

The RC3 catalogue (de Vaucouleurs et al. 1991) lists a large number of galaxies (more than 25000) distributed over the whole sky together with their morphological type. It is not fair to request that this huge catalogue be as good in selected regions as detailed studies of these regions. Furtermore, the galaxy types are not all based on the same observational material, but on a variety of plates, films, prints or copy of them, and have been assigned by different morphologists.

Because RC3 is the main catalogue of reference for types, and because morphological types are often claimed good if they agree with the ones listed in RC3 (e.g. Doi, Fukugita & Okamura 1993), we have to investigate how our types are related to the RC3 ones. A major caveat is in order: Coma galaxies are fainter than the majority of galaxies listed in RC3, and, as a consequence, we are making a comparison with the faint end of the catalogue only.

Among the 190 galaxies of our complete sample of galaxies in Coma, 129 are listed in RC3. Among those, only 71 have been assigned a definite morphological type in RC3, whereas 14 others have an uncertain morphological type. Limiting our sample to the magnitude of the faintest galaxy classified in RC3 (mag$_B$ = 16.3), 79 brighter galaxies (out of 158) are not classified (or listed at all) in RC3. This catalogue is therefore incomplete to a large degree for such faint galaxies. To reach a reasonable degree of completeness (90 %), RC3 has to be limited to mag$_B$ = 15.45, and in this case the sample of classified galaxies only numbers 53 galaxies.

Tables 6 and 7 show the comparison between our types and the ones listed in RC3 for the whole sample (mag$_B$ < 16.3) and for a brighter sample (mag$_B$ < 15.45) for which RC3 is 90 % complete. First of all, 60 % of the S0s are missing in RC3 whereas only 30 % of Es and 43 % of Ss are missing. The

missing galaxies are therefore not distributed uniformly among types. We stress again that these missing galaxies are brighter than the chosen magnitude limit.

The fraction of galaxies with discrepant types is 30 % for the two RC3 subsamples, a factor two higher than the value found for studies dedicated to the Coma cluster. A similar disagreement is found between RC3 and Dressler (27 %), based on 66 common galaxies. The disagreement between RC3 and SBD is similar to the one between us and BO, Dressler or RB (i.e. ~ 15 %).

RC3 agrees extraordinary well with BO and RB (less than 5 % of disagreement). This is inconceivable for two reasons. First, no pair of morphologists shows such a good agreement, and never does the RC3 type agree so well with de Vaucouleurs' estimate of the morphological type reported in Naim et al. (1995). Second, RC3 is a collection of types estimated by different morphologists. The only explanation for such a good agreement is that the morphological types of Coma galaxies in RC3 were taken from BO and RB.

In summary, RC3 is incomplete to a large degree in this region and for such faint galaxies, and, moreover, the missing galaxies are not distributed in a uniform way among types. Finally, one third of the galaxies with a morphological type in RC3 have discrepant types with respect to ours and Dressler's. Therefore, the use of this catalogue for morphological studies of nearby clusters is not recommended. Moreover, due to the high misclassification of the RC3 Coma sample of galaxies, this sample is not a good comparison sample to estimate the quality of other morphological classifications, as has unfortunately been done in the literature.

8. Redshift dependence of the classification

Up to now, we have compared our morphological types with those of traditional morphologists for *present day* galaxies. But how does the quality of our type estimates depend on redshift? Since the redshift does no enter at all in the classification skill, our expectation is that the quality of our Hubble estimates is as good for distant as for nearby galaxies, provided, of course, that the images of distant galaxies are as good as the nearby ones in terms of *rest-frame* resolution, sampling, depth, etc.

Distant ($z > 0.3$) clusters are now currently observed by *HST* and their galaxies are beginning to be classified by traditional morphologists. Dressler & Oemler classified the galaxies of the *distant* cluster Cl0939+4713 ($z \sim 0.4$) (Dressler et al. 1994b). For 31 galaxies, their type is listed in Stanford, Eisenhardt & Dickinson (1995). We re-classified the same galaxies from the same images (Andreon, Davoust & Heim, 1996). For these galaxies, we found the same rate of agreement (23 %) between our and Dressler & Oemler's classifications as for *nearby* galaxies. This result implies that the agreement between our classes and the traditional ones is not strongly redshift-dependent and that Dressler & Oemler classify distant galaxies in the same way as they classify nearby ones.

9. Conclusion

When our structural morphological scheme is reduced to the 3 coarse Hubble types and is applied to a sample of galaxies in the Coma cluster, it agrees to within 15 or 20% with other detailed traditional morphological analyses. This agreement is comparable to the one obtained among traditional morphologists. This shows that our criteria for classifying galaxies lead to the same results as the standard ones, and that our method is acceptable for classifying galaxies.

Most disagreements occur for galaxies difficult to classify because they are faint ($\mathrm{mag}_B > 16.0$), because images of higher resolution are required, and/or because of a disagreement on the significance of structural parameters in borderline cases between S0 and S.

At least half of the disagreements arise in spiral galaxies whose spiral arms (or spiral pattern) have not been detected or taken into account by previous analyses, even if S0/a galaxies are spirals by definition (e.g. BO, RC3 p. 15). Therefore traditional morphologists underestimate the spiral fraction in nearby clusters by 7 to 10 %. Even though this does not seem to be a large quantity, it represents an error of 100 % in the relative number of spirals in clusters, because of their scarcity with respect to early-type galaxies. This helps to resolve apparent differences between the number of spirals in nearby and distant clusters, for which various explanations and theories have been proposed in the recent past. At any rate, this underscores the need for higher resolution images as one classifies fainter and/or smaller galaxies.

The method we adopt uses quantitative criteria (the presence of structural properties) to classify galaxies, our types are thus reproducible and stable to a higher degree than the ones of morphologists. We also use better observational material for galaxies difficult to classify. The first results of analyses based on this method, summarized in Sect. 6.4, are promising. For all these reasons, our classification method should be preferred for classifying galaxies in clusters, even if it is more time and telescope consuming than the others.

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